Components Work Together To Cloak 'Shiny' Engine

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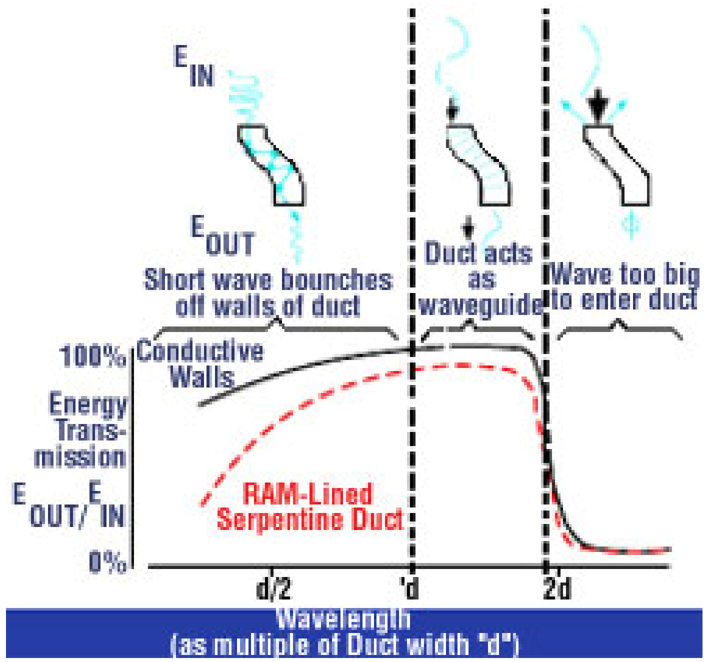
Techniques to reduce engine inlet and exhaust radar signature have been evolving during the last 40 years, from an add-on approach that leaves the engine untouched to a more integrated design where the fan may be altered to be part of a radar-foiling system.

Representative designs would be the SR-71 circa 1960, the F-117/Have Blue circa 1975, the F-22 and F/A-18E/F circa 1990 and the Joint Strike Fighter circa 2000.

Inlet and exhaust systems are perhaps the most crucial components in reducing radar reflection. They are aligned along the most tactically sensitive directions--to the front, where the enemy has time to see the aircraft coming and react, and to the rear, the area of the classic pursuit shot. And untreated, inlets and exhausts are often the most reflective part of an aircraft. Both act as cavity retroreflectors, with the inlet/exhaust duct carrying radar energy to a reflective compressor/turbine, and back out toward the radar.



"The front-aspect radar cross section of an F-15 is about 10 sq. meters, and of that about 10 sq. meters comes from the inlets," one stealth expert said. The F-15 inlets give a direct view of the compressor face and are good retroreflectors.

A KEY TO REDUCING inlet radar cross section (RCS) is understanding how radar waves travel through airflow ducts. This depends strongly upon the frequency, or wavelength, in relation to the duct width. When the wavelength is greater than twice the duct width, the wave is too large to enter and is reflected from the inlet (illustration, p. 93). The transmission of energy through the duct is essentially zero. A 3-ft.-wide duct would block waves greater than 6 ft. long, or frequencies below 150 MHz.

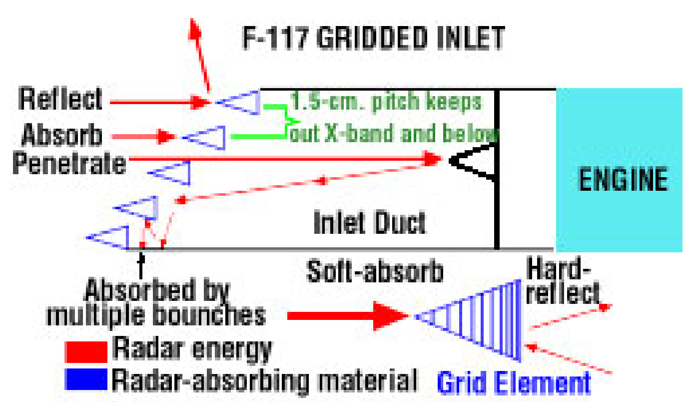
When the wave shrinks to 1-2 times the duct width, the duct becomes a waveguide and efficiently carries radar energy around corners with little loss. In this region, radar-absorbing material (RAM) lining the duct can only nip at the boundaries of the wave and has only moderate effect.

A wavelength that is substantially less than duct width tends to travel as in free space, bouncing off the walls like a beam of light. If the wall is conductive, the losses are fairly low; but if it is lined with RAM, the bounces cause strong attenuation.

The first aircraft designed at the outset to be stealthy was the German Horten IX, powered by two Junkers Jumo turbojets. A prototype flew in January 1945. The plywood skin was infused with carbon to absorb radar, and the flying wing planform was a first attempt at stealth shaping, but the engine faces were unprotected, though the exhaust exited in a trough on top of the wing like Northrop's B-2 bomber.

Lockheed's A-12 and SR-71 Blackbird reconnaissance aircraft also incorporated stealth from the beginning. The supersonic inlets had a large movable centerbody to control the flow, but the centerbody also created a thin annular duct that was too small for most radar wavelengths to enter. The centerbody was highly swept and bounced most radar waves away from their source. The tailpipes made good cavity retroreflectors, but Skunk Works engineers had a trick for that, too. It is not clear if this was ever operational, but a senior Skunk Works official said a fluid nicknamed "panther piss" could be injected into the exhaust. It would strongly ionize the exhaust, making it more reflective. While this might seem like a bad idea, actually it was good one. Radar waves from the rear would be blocked from making strong reflections from the tailpipe cavity, and instead would make weak scintillating reflections from the exhaust, the official said.

The stealthy nature of the Blackbirds seems to have been a well-kept secret, given the complete lack of stealth in fighter designs of the 1970s. Engineers had a chance again in the Defense Advanced Research Projects Agency/Lockheed Have Blue program that led to the F-117A. These aircraft were so secret that the engine companies were kept in the dark. General Electric F404s were quietly appropriated from the F/A-18 production line. All the stealth work was performed by the airframers, with the ground rule that they couldn't touch the engine itself. This resulted in add-on devices like the grilled inlets and platypus exhaust of the F-117.



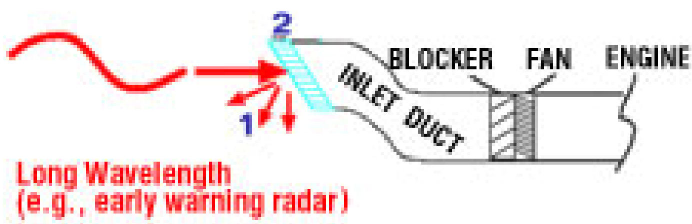
The inlet grills are like little ducts and have such a fine 0.6-in. pitch that most radar waves are too long to enter. The grills are made of graded RAM to absorb most energy, and are angled at more than 60 deg. to deflect remaining energy away from the front quarter. What energy does enter bounces off the engine face and duct, and has to exit through the grill. This is more difficult than entering because the graded RAM of the grill has an increasing resistance that is "soft" at the front for gradual absorption. But internal waves hit the "hard" backside and are reflected back into the duct where they are dissipated.

The price paid is loss of pressure across the grill, which reduces engine performance. But an offsetting benefit is that the grill acts as a flow straightener, providing undistorted air to the engine at angles up to 20 deg.

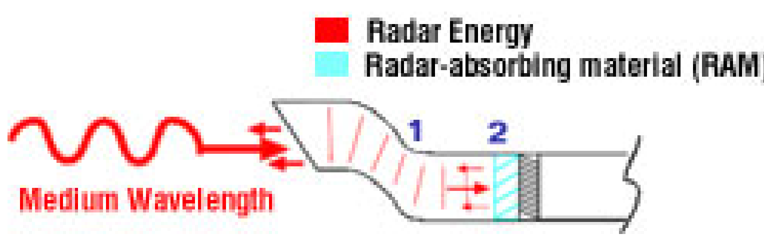
The F-117's thin platypus exhaust is canted up 10 deg. to prevent line-of-sight to the turbine face. A number of vertical vanes at the exit split it into a series of narrower ducts, keeping out longer waves as well as providing structural support and spreading the exhaust flow. The shorter wavelengths that enter quickly find themselves in a much larger duct once they get past the vanes, and make a number of bounces before they exit, hopefully losing energy. Given the high temperatures, it is unlikely the duct is lined with RAM, but there are high-temperature ceramic-based RAM tiles that are used at the exit.

Engine manufacturers were brought into the game by the time of the Air Force's Advanced Tactical Fighter (ATF) competition in the latter 1980s. A more integrated approach resulted--the engine was now modifiable, and interplay between engine and airframe companies gave a combination of engine and inlet design for low RCS with the least performance penalty.

A GRILLED INLET was unacceptable for a supersonic aircraft like the ATF and a different radar-defeating configuration was needed. The solution was the combination of a serpentine duct with a radar blocker on the front of the engine. With RAM tuned to certain wavelengths, this system could defeat a wide range of frequencies. When one component is acting like a waveguide, others are acting as absorbers. The range of threat wavelengths is about 2 meters (6.6 ft.) to 2 cm. (0.8 in.).



(1) Wave is too big to enter inlet, and reflects diffusely. Inlet is angled to reflect away from tactically-important directions.
(2) RAM treatment of inlet lip is tuned to absorb long wavelength and reduce reflection.
(3) Very little energy gets to blocker.



1. Wave is proper size for duct to acts as a wave guide and to carry energy unimpeded.
2. But wave is too big to enter spacing of blocker vanes. RAM coating on blocker is tuned to this frequency and absorbs most of the energy.
3. Small amount of energy is reflected back out the duct. Other techniques may be used to reduce this signature.

The radar blocker is essentially inlet guide vanes that have been shaped and treated with RAM to trap energy. The RAM coating is usually one-quarter wavelength thick. Wavelengths in high-dielectric RAM are much shorter than in free air, so a seemingly thin layer will suffice. Standard inlet guide vanes (IGVs) are thin to prevent pressure loss, and when modified into a radar blocker they are noticeably bulkier. RAM might add 1/16 in. to each side as well as changing the length and spacing of the vanes. Blocker IGVs may have been added to engines that didn't already have IGVs.

1. Wave bounces off walls of duct and is absorbed by RAM lining tuned to the high frequency.
2. Small amount of energy enters blocker, which acts as a wave guide at this frequency.
3. Wave exits blocker and hits fan, where energy is lost bouncing around blocker/fan labyrinth.
4. Energy escaping the blocker/fan trap loses more intensity as it makes multiple bounces out the inlet.

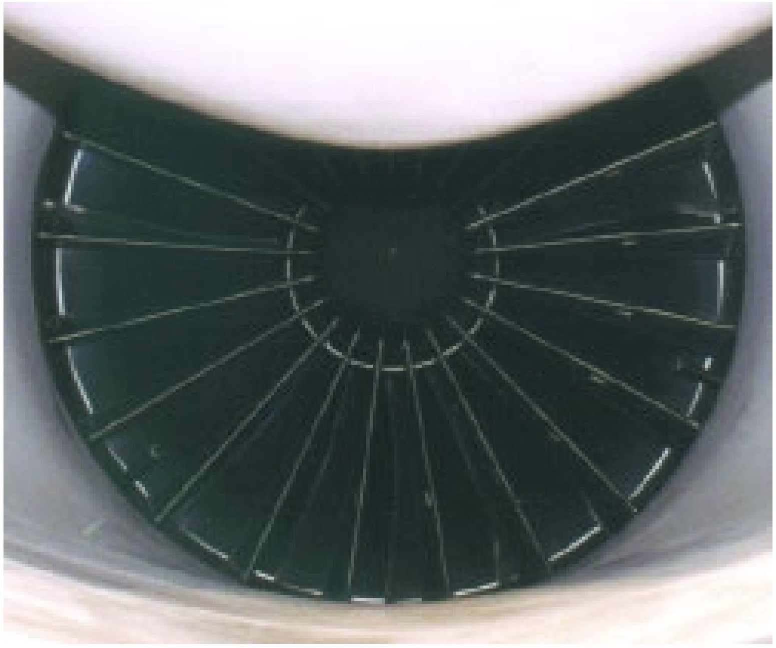
Engine purists are not happy about the changes. "The engine guy screams bloody murder," a stealth expert said. But on the F-22, "the blocker is critical to mission success," another industry official said.

Because radar waves behave in a fuzzier manner than rays of light, a blocker can be quite effective yet still allow optical line-of-sight to the fan face. In general, the amount of physical blockagevaries with the RCS specification, achieved usually by changing vane chord. However, the level of flow distortion seen by the compressor blades is also important, and the flow-smoothing effect of vanes with greater mixing length is a plus that can offset the pressure drop.

The relatively close spacing of the blocker vanes will keep out longer wavelengths, but the gaps are wide enough that they will act as waveguides at high frequencies. However, the scattering off the fan blades will cause some multi-bounce and loss of energy, and high frequencies also will be attenuated by multi-bounce in the RAM-lined inlet duct.

The engine manufacturers' approach until recently has been to design the rotating engine parts in a nonstealthy way and place radar-defeating duties on the IGVs. There is good reason for this. RAM coatings are more likely to stay attached on a stationary vane than on a high-speed fan. It is already difficult enough to design the crucial rotating components of a high-performance engine without having to worry about stealth considerations. And after investing billions in a new engine design, companies don't want to change internal components for every different aircraft application--it's easier to slap on a new blocker for each role.

Accordingly, a range of blockers should present consistent flow conditions to the fan face, especially angularity. One possible blocker/IGV configuration is S-shaped vanes that offset the flow to provide blockage with little angularity, but it is not clear if this has been implemented. The few that have been seen publicly seem to impart some twist to the flow.



Boeing X-32 relies on inlet guide vanes for major radar-absorbing role. The 18 fan blades are cloaked behind the 21 variable vanes, which can constrict for cruise.

McDonnell Douglas took an intermediate approach to reduce the signature of the F/A-18E/F by placing a vane-type blocker in the duct separate from the engine--see middle photo, p. 91 (*AW&ST* Sept. 25, 1995, p. 93). Boeing may be updating the design with an engine-mounted blocker.

Within roughly the last five years, the blocker has become an integral part of engine design, meaning that the fan is re-optimized for the angularity and pressure loss of an effective blocker. The Joint Strike Fighter has put this into practice. The Boeing X-32 and Lockheed X-35 entries are powered by different versions of the Pratt & Whitney JSF119 engine, with Boeing emphasizing fan thrust and Lockheed emphasizing shaft power extraction. The Boeing version has a larger fan.

BOEING FACES the more difficult inlet RCS challenge because its direct-lift configuration requires that the engine be far forward to place the lift nozzles near the center of gravity, leaving little length for a serpentine duct. About half the engine face is directly exposed by the 4-ft.-wide inlet, placing high demands upon the blocker. Because Pratt & Whitney had to build a special fan for the X-32 lift requirements, it is likely that this fan is matched to the X-32's heavy-duty blocker, and the X-35 fan is probably matched to what is likely a lighter duty blocker.

A clever technique is being used on the X-32--variable IGVs. For high power at low speed, the blocker vanes will twist open, but at cruise they will tighten to reduce RCS, as well as match pressure and flow rate with increasing Mach number.

The X-35 has smaller dual inlets that will block out higher frequencies than the X-32, as well as hiding the engine face. The X-35 inlets widen to a larger single duct that no longer acts as a waveguide, but instead causes attenuating multiple bounces--an effect similar to the splitter vanes in the F-117 exhaust.

The approach to modern exhaust systems is not different in principle from that to the inlets, with the addition of having to deal with high temperatures and differential expansion, a stealth expert said. Flow losses from an inlet-type blocker would be too high, but adding a few vanes that support the exhaust cone and arranging them to create some blockage might be effective. On the afterburning engines of the F-22 and JSF, clever arrangement of the afterburner flameholder rings could create useful radar blockage. Radar-absorbing ceramics may be effective, but they are not tough enough yet for rotating components.